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(71) Applicant (for all designated States except US): **QINETIQ LIMITED** [GB/GB]; Registered Office, 85 Buckingham Gate, London SW1E 6PD (GB).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **GORDON, Neil, Thomson** [GB/GB]; QinetiQ Limited, Malvern Technology Centre, St. Andrew's Road, Malvern, Worcestershire WR14 3PS (GB). **ELLIOTT, Tom** [GB/GB]; QinetiQ Limited, Malvern Technology Centre, St Andrew Road, Malvern, Worcestershire WR14 3PS (GB).

(74) Agent: **DAVIES, P**; IP QinetiQ Formalities, Cody Technology Park, A4 Building, Room G016, Ively Road, Farnborough, Hampshire GU14 0LX (GB).

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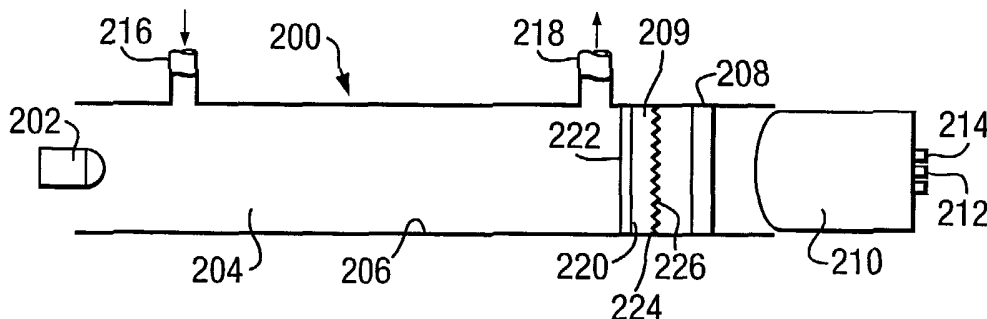
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(54) Title: SENSOR ARRANGEMENT AND METHOD OF SENSING



(57) Abstract: A sensor arrangement (200) comprises a radiation source (202), a sample cavity (204), a dispersive element (208) and first and second radiation detectors (212, 214). The radiation source (202) and the first and second radiation detectors (212, 214) are spaced apart about the sample cavity (204). The dispersive element (208) is located between the radiation source (204) and the radiation detectors (212, 214), such that, in use, radiation emitted by the radiation source (202) is spatially separated, by the dispersive element (208), into a first wavelength to be received by the first radiation detector (212) and a second wavelength to be received by the second radiation detector (214). A method of sensing a species of interest is also disclosed.

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SENSOR ARRANGEMENT AND METHOD OF SENSING

This invention relates to a sensor arrangement and a method of sensing. More particularly, but not exclusively, it relates to an infrared gas sensor
5 arrangement and a method of sensing a gas using an infrared sensor.

A typical current infrared gas sensor (100), as shown in Figure 1, comprises a radiation source (102), typically a heated filament with a strong emission in the infrared region, and a sample cavity (104) into
10 which gas is admitted via an inlet (106). The gas passes along the sample cavity (104), exiting via an outlet (108). Radiation emitted from the radiation source (102) passes along the cavity (104) and is absorbed by the gas at wavelengths characteristic of vibrational/rotational absorption bands of the gas. After passing through the gas the radiation passes
15 through a filter (110) arranged to be a bandpass filter allowing radiation through at one of the vibrational/rotational absorption bands of the gas. A data channel radiation detector (112) that detects radiation passing through the filter (110) is located on the opposite side of the filter (110) to the radiation source (102). Variations in the output of the radiation
20 source (102) make it desirable to use a reference, guard, channel (114) comprising a filter (116) arranged to pass radiation slightly offset in wavelength from that of the absorption band monitored by the data channel radiation detector (112) and a reference radiation detector (118). The reference channel (114) provides a normalisation signal for the data
25 channel.

Current sensor arrangements typically employ a thermopile sensor as large as 1mmx3mm. Due to their size they have appreciable internal noise which degrades both the data channel's and the reference channel's signal
30 to noise ratios, thereby reducing the accuracy of quantitative measurements. The efficiency of present sensor arrangements is limited

by the detector sensitivity, typically to a detectivity (D^*) of $1-2 \times 10^8 \text{ cm Hz}^{0.5} \text{ W}^{-1}$, and by the fact that the detector geometry is such that each detector collects only a fraction, approximately 8% and possibly as low as 1%, of the available radiation.

5

A further problem is the inherent risk in using of heated filaments in environments in which a flammable gas is present, for example an explosive atmosphere in a mine. The replacement of heated filaments with safer, less intense, radiation sources is limited by the poor detectivity of
10 current sensor arrangements.

Sensor arrangements have been produced in which accurately aligned optics are used to 'fold' the radiation through the sample cavity a number of times thereby increasing the effective optical pathlength through the
15 gas and increase the absorption, and sensitivity. Such arrangements are clearly expensive and difficult to manufacture due to the low tolerances in the optical alignment that is necessary.

According to a first aspect of the present invention there is provided a
20 sensor arrangement comprising:

a radiation source;

a sample cavity;

a dispersive element;

a focussing element; and

25 first and second radiation detectors;

the radiation source and the first and second radiation detectors being spaced apart about the sample cavity, and the dispersive element being located therebetween, such that, in use, radiation emitted by the radiation source is spatially separated, by the dispersive element, into a first
30 wavelength to be received by the first radiation detector and a second wavelength to be received by the second radiation detector, and the

focussing element being arranged to focus radiation at the first wavelength onto the first radiation detector and to focus radiation at the second wavelength onto the second radiation detector.

- 5 The spatial separation of the first and second wavelengths of radiation allows the overall size of the sensor arrangement to be reduced as the size of the detectors can be reduced because it is not necessary to gather radiation separately from different areas, as in the prior art. The same space in the device can contribute radiation to different spatially separated
10 sensors, dependent upon wavelength. This allows smaller, more portable sensor arrangements to be made.

The focussing element may be located between the dispersive element and the first and second detectors. The focussing element may be an
15 immersion lens, a field lens, a Fresnel lens, a zone plate, or a field immersion lens, for example. The zone plate may be etched onto a rear surface of the dispersive element. The focussing element enables radiation from a significantly larger area of space to be collected, concentrated, and focussed down onto a detector of smaller size. Having detectors of
20 smaller size has advantages. Collecting radiation from a wider area makes the sensor more sensitive.

There may be provided a second focussing element arranged to focus radiation emerging from the dispersive element different angles into
25 different focal positions prior to the first focussing element. This is useful in the case where an immersion lens is not used, as the detectors are not on the focal plane of the first focussing element. Therefore, the focussing of radiation from emerging from the dispersive element at different angles onto different areas requires the use of a separate lens.

The first and second detectors may be attached to the focussing element (or intimately optically coupled to it), typically in the case where the focussing element is a field immersion lens. The focussing element may form a substrate upon which the first and second detectors are epitaxially grown. This may be a good way of ensuring good coupling between the lens and the detector(s).

The use of a focussing element allows the dispersed radiation to be concentrated into a small area, as mentioned above. This produces an intense signal source, which increases the arrangement's signal to noise ratio and allows smaller detectors to be used. Smaller detectors are less prone to internal noise, which further increase the arrangement's signal to noise ratio due to their low level of internal noise.

The focussing element may be made from a high refractive index material, for example GaAs, Si, and Ge. Typically, the refractive index of the material of the focussing element is in the range of 3 to 5. Preferably the refractive index of the material of the focussing element is about 4, typically close to that of the detector. This minimises reflections at the lens-detector interface.

The focussing element may be a hemispherical immersion lens. Alternatively, the focussing element may be a hyper-hemispherical immersion lens. The apparent size of the detectors varies linearly with refractive index of the lens for a hemispherical immersion lens and as the square of the refractive index for a hyper-hemispherical immersion lens. Therefore, the detectors can collect more radiation for a given size of detector, which allows detector size to be reduced for a given sensitivity.

Having a lens which occupies the whole width of, or substantially the whole width of, the sample cavity may, at first sight, be thought to be a problem. If a lens (e.g. an immersion lens) occupies the whole of the

cavity and focuses parallel radiation in the cavity onto a single point – where the signal channel detector is located, where does one put the guard channel detector? It may be thought that there is no room in the sample chamber to have a guard channel detector, especially when the
5 prior art Figure 1 is considered (where the two detectors are side by side). However, using a dispersive element which directs radiation in an angular direction that is dependent upon wavelength allows a single focussing lens to focus different wavelength ranges onto different regions on the focal plane.

10 Hitherto, people have been careful in using sensors, for example gas sensors, to ensure that narrow band pass filters, with the pass notch centred on the absorption wavelength of interest, are disposed carefully substantially normally to sensors because it is well known that such filters are heavily angularly dependent and it is a problem that only light that is
15 more or less normal to the filter will actually be properly received by the detector. It has therefore previously been considered a problem to be overcome – the dispersive nature of band pass filters.

At least in one embodiment we have realised that a combination of a radiation-gathering focusing element capable of collecting radiation from
20 a wide area, and a wavelength dependent dispersive optical element can enable a detector to gather light at different wavelengths across the same area of space and focus the radiation at points (with an appropriate detector) that are spatially separated dependent upon the wavelength of light. Thus, it is possible to fit a guard channel detector within the area
25 of the device after all – because it is no longer the case that light from different regions of space falls upon the separate detectors.

The second detector may be substantially annular and may substantially surround the first detector. The first detector may be circular in cross-
30 section. The first detector may be located at the centre of the substantially annular second detector. An annular second detector will collect more of

the radiation at the second wavelength than a linear detector when the dispersed radiation is formed into an annulus-cone by the focussing element. Of course, if the focussing element and/or dispersive element combination produces a different wavelength dependent pattern of radiation (e.g. bars or stripes), the detector(s) may not be circular in nature, and could be, for example, linear.

The first detector may have a surface area of approximately 0.5mm^2 . The second detector may have a surface area of 0.5mm^2 .

10

The radiation source may be a light emitting diode (LED), typically with an output characteristic in the infrared region. Usually the output characteristic of the LED will include radiation at a wavelength of about $5\mu\text{m}$. Preferably the output characteristic of the LED will include wavelengths in the range $3\mu\text{m}$ to $11\mu\text{m}$. The output of the LED may be modulated, typically by switching the LED on and off. LEDs are advantageous to use over current hot filament radiation sources, as they can be modulated at high frequencies, are more stable and do not drift as much. An additional benefit of LEDs radiation sources in gas sensors is that they are cold sources and can therefore be used in the presence of flammable gases.

15
20

The LED may be optically coupled to a field immersion lens. The field immersion lens may be fabricated to match a field lens that is optically coupled with the first and second radiation detectors. The LED and field immersion lens may be arranged such that radiation emitted from the lens is emitted only at angles that lie within acceptance angles of the dispersive element. Thus, multiple reflections through the sample cavity do not change ray angles relative to the longitudinal axis of the sample cavity.

25
30

The dispersive element may be an interference filter, typically a Fabry-Perot interference filter. The filter may have a transmission function that is centred on an absorption band of a species or molecule of interest, which is either in the sample cavity or is to be admitted to the sample cavity, for a range of incidence angles. The dispersive element may be a diffraction grating. There may be a radiation diffuser located between the radiation source and the dispersive element. The radiation diffuser may be a plate of a high refractive index material, for example Ge, with a first face roughened, a typical roughness being 3-7 μ m peak to trough. A second face of the diffuser may have an anti-reflective coating thereupon. The radiation diffuser serves to randomise the incidence angle of the radiation upon the dispersive element. The dispersive element may be spaced some significant distance in front of the detector(s) to enable radiation that has been angularly deflected to different angles to separate to spaced apart spectral regions sufficiently for the detectors to be detecting different wavelengths.

Preferably, the first wavelength corresponds to a spectral absorption line of a species of interest. The first radiation detector may be arranged to operate as a data collection channel. Desirably, the second wavelength is spectrally separated from the absorption line of the species of interest. The second radiation detector may be arranged to operate as a reference, or guard, channel.

The first wavelength of radiation may be spectrally separated from the second wavelength of radiation such that there is slight overlap (at the sensors) between respective spectral lines associated with the first and second wavelengths. However, the spectral lines will be separated enough to enable the main detector and guard channel detector to generate properly. Preferably, the first wavelength of radiation is spectrally separated from the second wavelength of radiation such that there is no,

or substantially no, overlap between the respective spectral lines associated with the first and second wavelengths. This limits, or ideally eliminates, contributions to the detection signal from the guard, reference signal.

5

Conveniently the sample cavity is arranged to hold a fluid. The fluid may be a gas. The fluid may contain a species of interest. The species of interest may be any one, or more, of the following: CH₄, H₂S, CO, CO₂, and SO₂. These are typical atmospheric pollutants (and atmospheric pollution monitoring equipment is a desired area of application for the technology). A typical wavelength for absorption for these kinds of molecules is about 5μm, and a typical filter might be at 5.1μm, with a guard channel at about 5.15μm.

Desirably at least the first radiation detector has a detectivity (D*) of at least $1 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$. More at least the first radiation detector has a detectivity of at least $4 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$. Preferably at least the second radiation detector has a detectivity (D*) of at least $1 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$. More at least the second radiation detector has a detectivity of at least $4 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$. Such a high sensitivity allows the threshold of detection of the sensor arrangement to be achieved with less of the species of interest present than is currently the case for a given design of detector arrangement. The high sensitivity of the arrangement also reduces output power of the radiation source necessary to achieve the detection threshold. Additionally, this also removes the need for folded optics to increase the effective optical path length that is used in some current detectors.

According to second aspect of the present invention there is provided a method of sensing a species of interest comprising the steps of:

- i) providing radiation at a first wavelength corresponding to a spectral absorption band of a species or molecule of interest and at a second wavelength;
- ii) passing the radiation through a sample cavity;
- 5. iii) separating the radiation at the first and second wavelengths spatially, by means of a dispersive element;
- iv) focussing the radiation at the first and second wavelengths, by means of a focussing element; and
- v) detecting the radiation at the first and second wavelengths, by
10 means of respective first and second radiation detectors arranged at different spatial positions.

The method may include focussing the radiation at the first and second wavelengths by, means of a focussing element. The method may include
15 providing the focussing element in the form of any one, or combination, of the following: immersion lens, field lens, Fresnel lens, field immersion lens.

The method may include attaching, or intimately coupling, the first and
20 second detectors to the focussing element. The method may include growing the first and second detectors upon the focussing element, epitaxially. A couplant (e.g. glue) may be used to attach the detector to the focussing element (e.g. lens).

25 The method may include producing the focussing element from a high refractive index material, for example GaAs, Si, and Ge. The method may include providing a focussing element with a refractive index in the range of 3 to 5. Desirably the method includes providing a focussing element with a refractive index which is close to that of material of the
30 radiation detector material, typically about 4.

The method may include providing the radiation source in the form of a light emitting diode (LED), typically with an output characteristic in the infrared region. The method may include outputting radiation at a wavelength of about $5\mu\text{m}$ from the LED. The method may include
5 outputting radiation at wavelengths in the range $3\mu\text{m}$ to $7\mu\text{m}$ from the LED. The method may include modulating the output of the LED (e.g. with a chopper). The method may include switching the LED on and off.

The method may include providing the dispersive element in the form of
10 an interference filter, typically a Fabry-Perot interference filter. The method may include transmitting radiation centred on an absorption line of a species of interest through the filter. The method may include providing the dispersive element in the form of a diffraction grating. The method may include diffusing the radiation between the radiation source
15 and the dispersive element.

The method may include collecting qualitative data about the presence of the species of interest in the sample cavity at the first radiation detector. The method may include collecting quantitative data about the amount of
20 the species of interest present in the sample cavity at the first radiation detector. The method may include collecting reference (guard) data at the second radiation detector.

The method may include providing radiation in which the first and second
25 wavelengths of radiation are spectrally separated such that there is slight overlap therebetween. The method may include providing radiation in which the first and second wavelengths of radiation are spectrally separated such that there is no, or substantially no, overlap therebetween.

30 The method may include filling the sample cavity, at least partially, with a fluid. The method may include filling the sample cavity at least partially

with a fluid that contains the species of interest. The method may include providing the fluid in the form of a gas. The species of interest may be any one, or more, of the following: CH₄, H₂S, CO, CO₂, and SO₂. A solid may be tested in the cavity. Granules, or a powder (e.g. flowable
5 solid) may be tested.

Desirably the method includes providing either, or both, of the first and second radiation detectors having a detectivity (D*) of at least $1 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$. More desirably the method includes providing either, or both,
10 of the first and second radiation detectors having a detectivity of at least $4 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$.

According to a third aspect of the present invention there is provided a sensor arrangement comprising:
15 a radiation source;
a sample cavity;
a focussing element; and
first and second radiation detectors;
the radiation source and the first and second radiation detectors being
20 spaced apart about the sample cavity, and the focussing element being located therebetween, such that, in use, radiation of a first wavelength emitted by the radiation source is focussed onto the first radiation detector and radiation of a second wavelength emitted by the radiation source is focussed onto the second radiation detector.

25 The focussing element may be an immersion lens, a field lens, a Fresnel lens, a field immersion lens. The first and second detectors may be attached to the focussing element, particularly in the case where the focussing element is an immersion lens. The focussing element may form
30 a substrate upon which the first and second detectors are epitaxially grown.

The arrangement may include a dispersive element, for example an interference filter, located between the radiation source and the radiation detectors.

5

According to a fourth aspect of the present invention there is provided a radiation source arrangement, suitable for use is a sensor arrangement, comprising:

a light emitting diode (LED); and

10 a focussing element;

the LED being optically immersed with the focussing element such that radiation emitted by the LED forms substantially parallel beams upon emerging from the focussing element.

15 Desirably the focussing element is a field lens. Advantageously the radiation emerging from the focussing element is constrained within acceptance angles of a dispersive element. Such an emission arrangement has similar advantages to those discussed in relation to optical immersion of radiation detectors.

20

The invention will now be described, by way of example only, with reference to the accompanying drawings and table in which:

Figure 1 is a gas sensor arrangement of the prior art;

25

Figure 2 is a side view of a sensor arrangement according to the present invention;

Figure 2a is a partial side view of an emission arrangement
30 suitable for use with the sensor arrangement of Figure 2;

Figure 3 is a schematic view of a filter, lens and detector of the sensor arrangement of Figure 2;

5 **Figure 4** is a representation of the propagation of radiation across a Fabry-Perot interference filter;

Figure 5 is a plot of the transmission of infrared radiation across a Fabry-Perot interference filter for two groups of incidence angles;

10 **Figure 6** is a representation of a field immersion lens;

Figure 7 is a table of sensitivity calculations for a sensor arrangement according to an aspect of the present invention; and

15 **Figure 8** is a flow chart detailing a method of sensing a species of interest according to an aspect of the present invention.

Referring now to Figures 2 and 3, a sensor arrangement 200, comprises a radiation source 202, typically an LED, a sample cavity 204 in the form
20 of a plain cylindrical tube of circular cross-section having a reflective inner surface 206, an interference filter 208, typically a Fabry-Perot filter, a radiation diffuser 209, a field immersion lens 210, a data radiation detector 212 and a guard radiation detector 214. The sample cavity 204 has a gas inlet 216 and a gas outlet 218.

25

In use, a gas, typically containing a species of interest, is admitted to the sample cavity 204 via the inlet 216. The gas is typically admitted under pressure, either via a pumping arrangement or from a pressurised cylinder, or is allowed to diffuse into the sample cavity 204, for example
30 from the surrounding atmosphere. Alternatively, a pumping arrangement

may be attached to the outlet 218 and the gas is drawn through the sample cavity 204 via the inlet 214.

The radiation source 202 emits radiation, typically including wavelengths
5 from 3-11 μ m. The radiation passes along the sample cavity 204 being reflected off the wall 206. Wavelengths within the radiation corresponding to vibrational/rotational absorption bands within the gas are attenuated by the gas more than wavelengths that do not correspond to such absorption bands.

10

Radiation passes through the radiation diffuser 209, which is typically a disc of a high refractive index material, such as Ge. A surface 220 of the diffuser 209 nearest the radiation source 202 has an anti-reflective coating
15 222 thereupon and a surface 224 of the diffuser 209 nearest the interference filter 208 has asperities 226 of the order of a few microns thereupon. The diffusion of the radiation counteracts non-uniformities in the radiation source 202 and also non-uniformities in reflections of radiation from the inner surface 206 of the sample cavity 204.

20 Radiation exiting the diffuser 209 passes to the interference filter 208, which typically has a transmission function that is centred on the vibrational/rotational absorption band of interest of the gas.

Referring now to Figure 2a, LED 202 is in optically coupled to a lens
25 228, typically a field immersion lens, such that light emitted by the LED 202 is focussed into a limited range of angles. This results in the majority of the light emitted by the LED 202 radiating from the lens 228 in directions that are useful in the collection of data.

30 In the case where LED 202 and a field lens 228 are used in conjunction with the detection arrangement of Figure 2, radiation emitted from the

LED 202 can be matched to the field lens 210 such that the emitted radiation is within the acceptance angle of the dispersive element 208. Thus, substantially all of the radiation emitted by the LED 202 at the wavelengths of interest is detected at the respective first and second
 5 radiation detectors 212, 214. Also, using this emission arrangement multiple reflections through the sample cavity 204 do not change ray angles relative to the longitudinal axis of the sample cavity 204. This contrasts to the use of a filament source where light is radiated in directions that are unusable in terms of data collection.

10

Referring now to Figures 4 and 5, a simple Fabry-Perot filter 400, with a refractive index n_r and width d , has been assumed in which radiation 402, with a wavelength λ , enters the filter 400 from air at an incidence angle Ψ_1 . The radiation 402 is refracted on entry into the filter 400 to an angle
 15 Ψ_2 .

The transmission of the filter is:

$$T = \frac{1}{1 + \frac{4R^2}{(1-R^2)^2} \cdot \sin^2 \frac{\delta}{2}}$$

20

Where:

$$\delta = \frac{4\pi}{\lambda} \cdot n_r d \cos(\psi_2)$$

25 and

$$\psi_2 = \arcsin \left[\frac{\sin(\psi_1)}{n} \right]$$

Thus, different wavelengths of radiation are spatially separated by the interference filter, as shown in Figure 5. The flux output from the filter 208 that falls upon the data radiation detector 212 is given by:

$$S1 = K \int_{\lambda_1}^{\lambda_2} \int_0^{\theta} T(\lambda, \psi) \sin(\psi) \cos(\psi) \delta\psi \delta\lambda$$

5

The flux output from the filter 208 that falls upon the guard radiation detector 214 is given by:

$$SG = K \int_{\lambda_1}^{\lambda_2} \int_{\phi_1}^{\phi_2} T(\lambda, \psi) \sin(\psi) \cos(\psi) \delta\psi \delta\lambda$$

Figure 5 shows plots of these integrands over ψ for a signal channel centred on a wavelength of $4.25\mu\text{m}$, the peak of a CO_2 absorption band, versus wavelength. The calculations upon which these plots are based were carried out for a CaF_2 ($d=3.02\mu\text{m}$ and $n_r=1.42$) interference filter of approximately one wavelength thickness at normal incidence, i.e. $m=2$ and $\theta=90^\circ$ in the equation $m\lambda=2d\sin\theta$. The dotted line 502 represents the data radiation detector signal and corresponds to radiation received in a cone of between 0 and 14 degrees from the normal. The solid line 504 represents the guard radiation detector signal and corresponds to radiation received in a cone of between 19 and 24 degrees from the normal. The separation of the peak positions of the plots 502 and 504 demonstrates that radiation of different wavelengths is spatially separated by the interference filter 208. In an ideal arrangement there would be no overlap of the tails of the peak position of the guard channel and data channel signals. This can be obtained by increasing the value of m or by varying the angle of the cones in which the signals are received.

25

Upon exiting the interference filter 208 the radiation passes to the field immersion lens 210. The lens 210 can be regarded as forming an image of an object at infinity on the radiation detectors 212, 214 on its output plane. The effect of this is to bring parallel beams of infrared radiation at
 5 different angles to a focus at different radii.

Referring now to Figure 6, a lens 600 has an annular, outer radiation detector 602 and a circular, inner radiation detector 604 on an output plane 606 thereof. The detectors 602, 604 can be epitaxially grown onto
 10 the lens 600 which acts as a substrate for growth purposes. Typical materials for the lens are GaAs, Si or Ge and the detectors may be $\text{HgCd}_{1-x}\text{Te}_x$ or InSb.

Thus the inner detector receives 604 radiation from a cone of angles between 0 and θ , and the outer detector 602 receives radiation from a
 15 cone of angles between ϕ_1 and ϕ_2 .

The lens 600 has a focal length given by:

$$f = \frac{n}{n-1} \cdot r$$

20 Where: n = refractive index of the lens
 r = radius of curvature of lens surface

$$a = f \cdot \arcsin \left[\frac{\sin(\theta)}{n} \right]$$

$$b = f \cdot \arcsin \left[\frac{\sin(\phi_1)}{n} \right]$$

$$c = f \cdot \arcsin \left[\frac{\sin(\phi_2)}{n} \right]$$

As an example, the following parameters have been used;

5 $d = 3.5\text{mm}$
 $n = 4$
 radius of curvature, $r = 5\text{mm}$

10 This gives $f = 6.7 \text{ mm}$.

The cone angles were chosen as:

$\theta = 14 \text{ degrees}$
15 $\phi_1 = 18 \text{ degrees}$
 $\phi_2 = 23 \text{ degrees}$

The resulting detector sizes are;

20 Signal detector diameter, $2a = 0.81\text{mm}$
 Guard detector inner diameter, $2b = 1.04 \text{ mm}$
 Guard detector outer diameter, $2c = 1.31 \text{ mm}$

The maximum area gain for the example system incorporating the filter 400
25 detailed with reference to Figures 4 and 5, and the lens 600 detailed with
reference to Figure 6 is the square of the lens diameter over the signal detector
diameter, which in this case is 144, giving a potential sensitivity improvement of
12. In practice the maximum gain will be limited either by optical aberrations or
for the case where the lens is glued to the detector by the requirement to keep
30 most of the radiation within the critical angle at the lens/glue interface.

Using an immersion lens to yield a large optical gain requires the radiation to be bent through very high angles. In the case where the detector is glued to the focal plane of the lens, radiation received at above the critical angle of the lens/glue interface will be reflected unless the
5 thickness of the glue layer is less than about $\lambda/10$, where λ is the wavelength of the incident radiation. Generally, the lens is designed such that most of the radiation is within the critical angle of reflection. In the case where there is no glue layer, true immersion, for example when the detector is grown onto the lens, epitaxially or otherwise, the above
10 considerations are moot.

Referring now to Figure 7, this shows detectivity values calculated for a radiation detector at varying radii of curvature of a field immersion lens,
15 as can be seen from the equations above the focal length of the lens and the data detector and guard detector sizes will vary with the radius of curvature of the lens. The arrangement includes an interference filter having a refractive index of 1.42, a data radiation detector receiving radiation in a cone between 0° and 14° relative to the normal, a guard
20 radiation detector receiving radiation in a cone between 19° and 24° . The detectors are modelled as InSb/InAlSb heterostructures. The diameter of the sample cavity tube and the field immersion lens are both taken to be 7mm.

25 The detectivity is shown for an uncooled 295K detector with an ideal, noiseless, amplifier and with a practical amplifier based upon LT1028 amplifier chips (Linear Technology Corporation). Detectivity is also shown for detectors cooled to 250K with a Peltier cooler. Detectivity values are shown for single stage and six parallel stage LT1028s.

The detectivity of the above described sensor arrangement at 250K with a six stage amplifier and a radius of curvature of 5mm is approximately $1 \times 10^{10} \text{ cm Hz}^{0.5} \text{ W}^{-1}$. This is 50 to 100 times greater than the sensitivity of a thermopile at the same temperature and amplification.

5

The above described sensor arrangement also collects radiation more efficiently than current arrangements. Assuming a lens transmission of 50% and a 20% loss of area in order to increase detector separation each detector collects 40% of the available radiation, which is a 5 fold improvement over a typical thermopile sensor arrangement.

10

Thus, the above described sensor arrangement yields an overall sensitivity improvement of 200 to 500 times over a typical thermopile sensor arrangement.

15

The increase in sensitivity allows more rapid data acquisition than is currently the case. This is important in medical diagnosis of, for example, diabetes where acetone is detected on a patient's breath.

Referring now to Figure 8, a method of sensing a species of interest comprises providing radiation at a first wavelength corresponding to a spectral absorption band of the species of interest and at a second wavelength (Step 800). The radiation is passed through a sample cavity (Step 802). The radiation at the first and second wavelengths is spatially separated by means of a dispersive element (Step 804). The radiation at the first and second wavelengths is detected by means of respective first and second radiation detectors (Step 806).

20

25

It will be appreciated that although described with reference to the sensing of gases the sensor arrangement described hereinbefore may be used to sense a species of interest in a liquid or a solid with appropriate

30

modifications to the sample cavity. It will also be appreciated that the primary field of use is as a gas sensor.

It will be appreciated that by having a lens across the full width of the cavity we collect the maximum light possible, and by having the lens/dispersive element combination focus light of different wavelengths onto different physical positions in the back plane of the lens we spatially separate light of different wavelengths, thereby allowing different sensors to detect light of different wavelengths – with that light having come from the same volume of space in front of the lens. This enables good sensitivity/fast response time.

It will be appreciated that for some embodiments the use of the filter as a wavelength dependent angle disperser of light, for off axis light, is important. This feature of filters is normally considered to be a problem, but we turn it to our advantage.

It will also be appreciated that although the application above is written so as to discuss detectors, the rays of radiation are reversible and it is possible to have emitters that emit radiation, with emitters being placed at different spatial positions and using a lens/angle-dependent diverter of the light to divert light of particular wavelengths by different angles. However, the primary area of application of the invention is intended to be detectors.

It will also be appreciated that the sensitivity of the device is dependent upon the power of the emitter, and that we can have a more sensitive device, or a lower power emitter, or both. Similarly, the sensitivity of the device depends upon the path length of light within the chamber, and so we can have a shorter tube/chamber, or a more sensitive device. It is because our device is more sensitive that we can use an LED

satisfactorily, which has hitherto not been a viable option. LEDs are safer, it is possible to modulate their light to get better signal to noise ratio, they are fast to warm up, they are cheap, they are more stable than many other light sources, and they last longer. Thus our devices can last
5 longer/have a greater useful life before repair. We may have an immersed emitter, possibly with angles of emission that are matched to an appropriate dispersion element for the emitter.

Another feature is that it will be appreciated that we use only one filter –
10 in comparison with the prior art of Figure 1 which uses two filters.

Furthermore, we have only one detector assembly (especially when detectors are attached to/grown on the back of a lens), in comparison with the prior art which has two separate detectors, and the detector assembly
15 may be fabricated in one single manufacturing operation, which is better/cheaper than forming two operations.

The speed of response of our device is better, because it has a better signal to noise ratio (and therefore we can use a greater bandwidth, obtaining a better speed of response). In areas where it is desirable to
20 detect chemical components swiftly this can be very useful.

An aspect of the invention could be considered to be a method of improving the performance of a sensor, especially a gas sensor, and that
25 performance may constitute one or more of:

- improving sensitivity,
- reducing power needed for the emitter,
- reducing the length of the chamber,
- reducing the time taken to perform a test.

30

Having the immersed detectors is very helpful to sell embodiments.

CLAIMS

1. A sensor arrangement comprising:
a radiation source;
5 a sample cavity;
a dispersive element;
a focussing element; and
first and second radiation detectors;
the radiation source and the first and second radiation detectors being
10 spaced apart about the sample cavity, and the dispersive element being
located therebetween, such that, in use, radiation emitted by the radiation
source is spatially separated, by the dispersive element, into a first
wavelength to be received by the first radiation detector and a second
wavelength to be received by the second radiation detector, and the
15 focussing element being arranged to focus radiation at the first
wavelength onto the first radiation detector and to focus radiation at the
second wavelength onto the second radiation detector.
2. An arrangement according to Claim 1 wherein the focussing
20 element is located between the dispersive element and the first and second
detectors.
3. An arrangement according to either of Claims 1 or 2 wherein the
focussing element is intimately optically coupled to the first and second
25 detectors.
4. An arrangement according to any preceding claim wherein the
focussing element is an immersion lens.

5. An arrangement according to any preceding claim wherein the second detector is substantially annular and substantially surrounds the first detector.
- 5 6. An arrangement according to any preceding claim wherein the radiation source is a light emitting diode (LED).
7. An arrangement according to Claim 6 wherein the LED is optically coupled to a field immersion lens.
- 10 8. An arrangement according to Claim 7 wherein the field immersion lens is fabricated to match a field lens that is optically coupled with the first and second radiation detectors.
- 15 9. An arrangement according to either of Claims 7 or 8 wherein the LED and field immersion lens are arranged, such that radiation emitted from the lens is emitted only at angles that lie within acceptance angles of the dispersive element.
- 20 10. An arrangement according to any preceding claim wherein the dispersive element is an interference filter.
11. An arrangement according to Claim 10 wherein the filter has a transmission function that is centred on an absorption line of a species of
- 25 interest for a range of incidence angles.
12. An arrangement according to any preceding claim wherein there is a radiation diffuser located between the radiation source and the dispersive element.

13. An arrangement according to any preceding claim wherein the first wavelength corresponds to a spectral absorption line of a species of interest and the first radiation detector is arranged to operate as a data collection channel.

5

14. An arrangement according to any preceding claim wherein the second wavelength is spectrally separated from the absorption line of the species of interest and the second radiation detector is arranged to operate as a reference channel.

10

15. An arrangement according to any preceding claim wherein the sample cavity is arranged to hold a gas.

16. An arrangement according to any preceding claim wherein at least one of the first or second radiation detectors has a detectivity (D^*) of at least $1 \times 10^9 \text{ cm Hz}^{0.5} \text{ W}^{-1}$.

17. A method of sensing a species of interest comprising the steps of:

- i) providing radiation at a first wavelength corresponding to a spectral absorption band of a species or molecule of interest and at a second wavelength;
- ii) passing the radiation through a sample cavity;
- iii) separating the radiation at the first and second wavelengths spatially, by means of a dispersive element;
- iv) focussing the radiation at the first and second wavelengths, by means of a focussing element; and
- v) detecting the radiation at the first and second wavelengths, by means of respective first and second radiation detectors provided at different spatial positions.

30

18. The method of Claim 17 including providing a focussing element with a refractive index in the range of 3 to 5.
- 5 19. The method of either one of Claims 17 or 18 including providing the radiation source in the form of a light emitting diode (LED).
20. The method of Claim 19 including outputting radiation at wavelengths in the range $3\mu\text{m}$ to $11\mu\text{m}$ from the LED.
- 10 21. The method of either of Claims 19 or 20 including optically immersing the LED with a field lens.
22. The method of any one of Claims 17 to 21 including providing the
15 dispersive element in the form of an interference filter.
23. The method of Claim 22 including transmitting radiation centred on an absorption line of a species of interest through the filter.
- 20 24. The method of any one of Claims 17 to 23 including filling the sample cavity, at least partially, with a gas containing the species of interest.
25. A sensor arrangement comprising:
25 a radiation source;
a sample cavity;
a focussing element; and
first and second radiation detectors;
the radiation source and the first and second radiation detectors being
30 spaced apart about the sample cavity, and the focussing element being located therebetween, such that, in use, radiation of a first wavelength

emitted by the radiation source is focussed onto the first radiation detector and radiation of a second wavelength emitted by the radiation source is focussed onto the second radiation detector.

- 5 26. A radiation source arrangement, suitable for use is a sensor arrangement, comprising:
- a light emitting diode (LED); and
- a focussing element;
- the LED being optically immersed with the focussing element such that
- 10 radiation emitted by the LED forms substantially parallel beams upon emerging from the focussing element.

Fig.1.

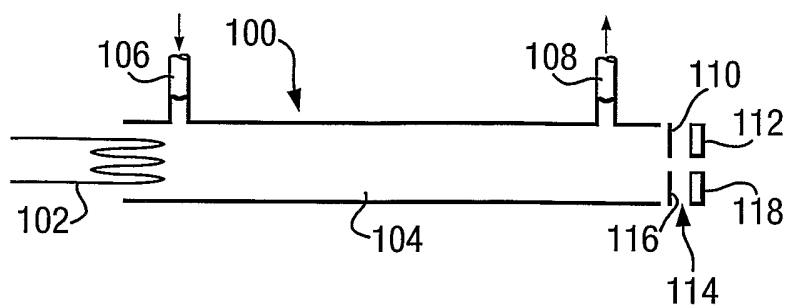


Fig.2.

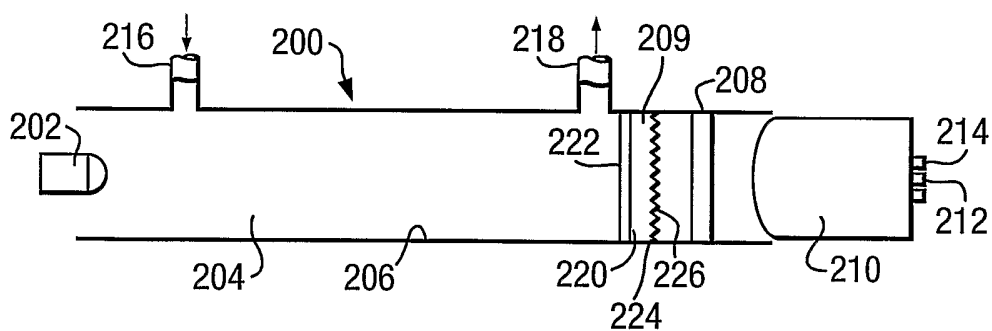
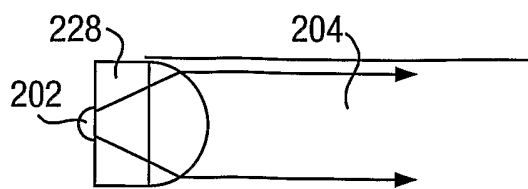


Fig.2a.



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Fig.3.

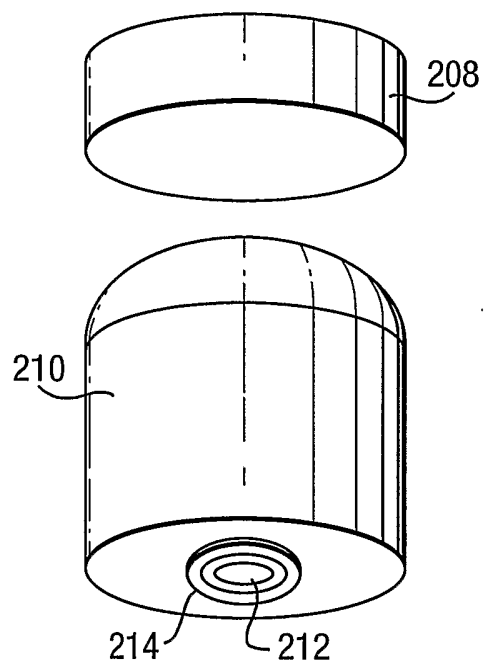


Fig.4.

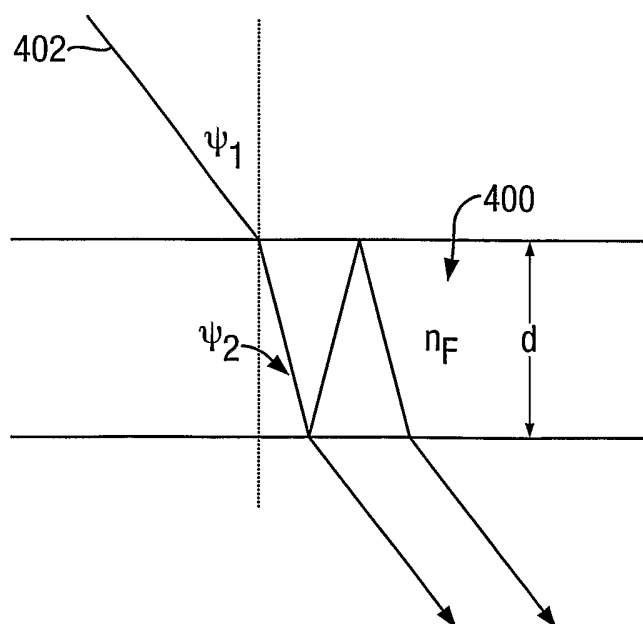
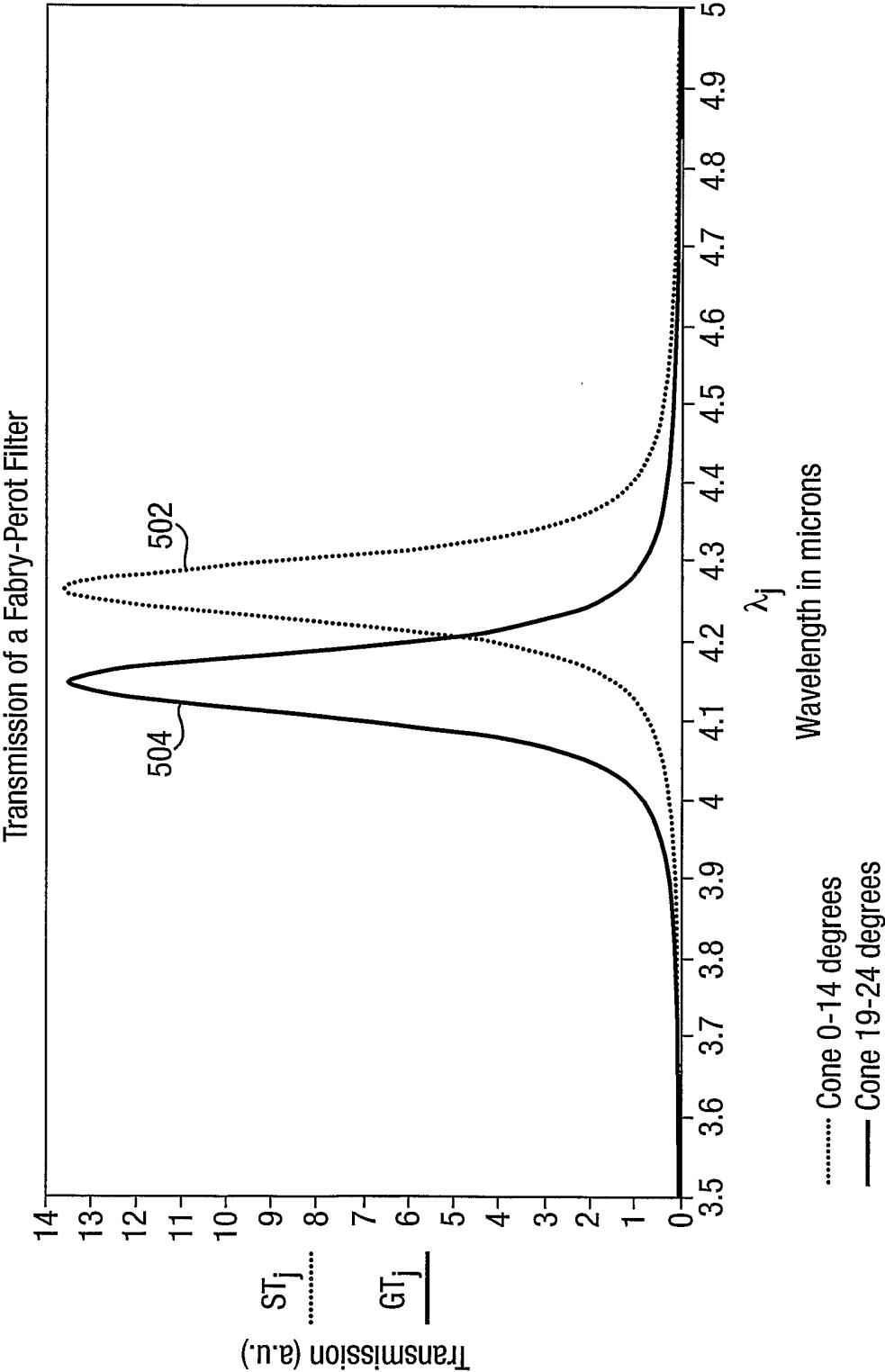


Fig.5.



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Fig.6.

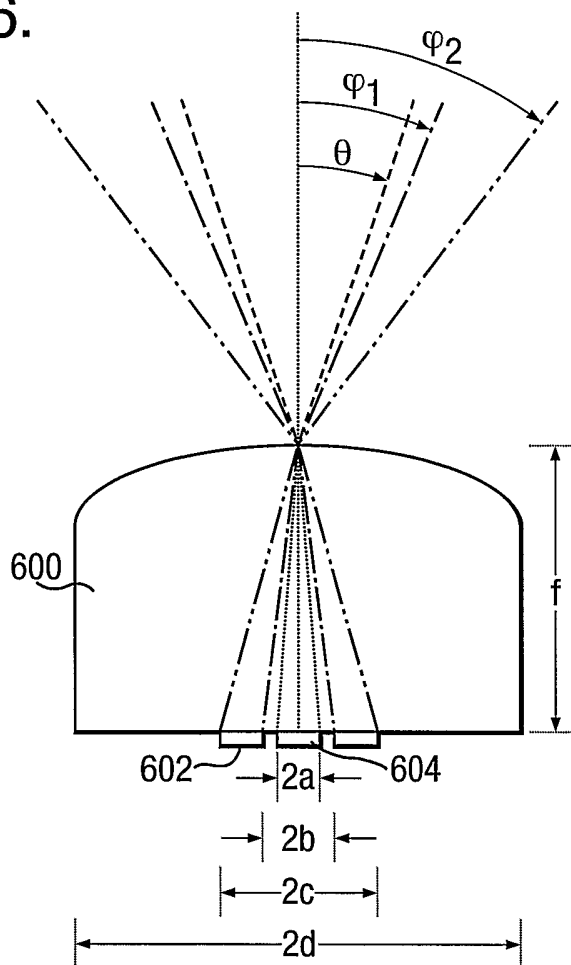
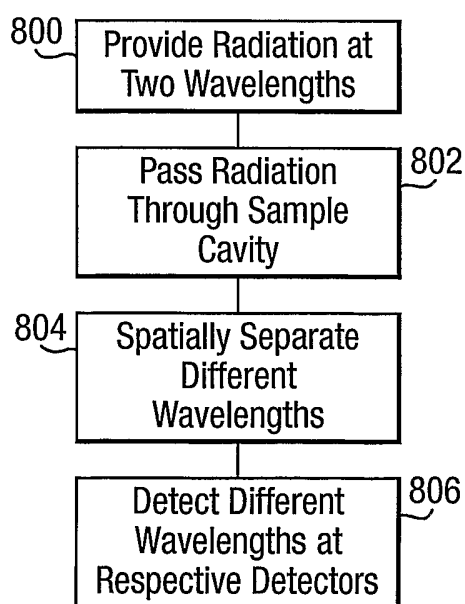


Fig.8.



INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 03/03520

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 G01N21/35 G01N21/31

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 G01N G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, COMPENDEX, INSPEC, PAJ, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 01 13091 A (UNIV MINNESOTA) 22 February 2001 (2001-02-22) page 18, line 12 - page 19, line 24 page 21, line 18 - line 20	1, 2, 15, 17, 24
Y	page 25, line 6 - line 31 figures 4, 7A-7C	3, 4, 6-14, 16, 18-23
X	EP 0 254 879 A (KERNFORSCHUNGSZ KARLSRUHE) 3 February 1988 (1988-02-03) figure 1 column 3, line 30 - line 41 column 4, line 54 - line 57 -/--	1, 15, 17, 24, 25



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

° Special categories of cited documents :

A document defining the general state of the art which is not considered to be of particular relevance

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O document referring to an oral disclosure, use, exhibition or other means

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T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

* & * document member of the same patent family

Date of the actual completion of the international search

22 December 2003

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Verdoodt, E

INTERNATIONAL SEARCH REPORT

Intern al Application No

PCT/GB 03/03520

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SMITH S D ET AL: "UPDATE ON ALL-SOLID-STATE INFRARED GAS SENSORS: PROGRESS IN LED'S AND MINIMALLY COOLED INFRARED DETECTORS" SENSOR AND TRANSDUCER CONFERENCE. MTEC - THE UK'S EXHIBITION FOR SENSORS. MEASUREMENT AND CONTROL, XX, XX, vol. 1, 2000, pages 1-5, XP008025163 the whole document -----	3
A	EP 1 061 355 A (INSTRUMENTARIUM CORP) 20 December 2000 (2000-12-20) the whole document -----	1

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